An Increased-Sensitivity Micro Volt-Ammeter Using A Photoconductive Chopper

TWO OF THE paramount considerations in designing a dc microvoltmeter are minimizing noise so that high sensitivity can be obtained and then achieving freedom from drift on the resulting sensitive ranges. In general, freedom from drift is usually sought by using mechanical choppers to permit an ac-coupled amplifier to be used, while low noise is sought by heavily restricting the bandwidth of the amplifier. Using mechanical choppers is expensive, however, and often introduces other sources of noise into the amplifier. In addition and more important from a measurement standpoint, if line frequencies are used to drive the chopper, as is almost always the case, the measurements are susceptible to large errors when line-frequency hum is present in the dc voltage or current being measured.

The new dc micro volt-ammeter shown in Fig. 1 achieves higher sensitivity and lower drift than established designs by using a non-mechanical chopper consisting of long-life photoconductor elements. The modulator is operated at other than line frequency so that extremely low effect from 60- and 120-cycle ripple in the measured dc is obtained. Negligible zero drift is obtained by meticulous attention to overall design, while calibration is stable and accurate because of feedback. The resulting instrument has a maximum full-scale voltage sensitivity of ±10 microvolts and a full-scale current sensitivity of ±10 micro-amperes combined with a high input impedance for voltage measurements and a drift of not more than 1 microvolt per hour. Under usual operating conditions, drift is less than 1 microvolt over a period of several hours. The instrument also has a floating input, a factor that has special advantages in the microvolt region, as described later.

The basic power sensitivity of the instrument is better than $10^{-18}$ watt, which, for an
acceptable speed and noise level, is an advance in the art for a high-impedance instrument. In voltage and current terms, a dc measuring instrument capable of measuring 10 microvolts or 10 micro-microamperes full scale increases the measurement threshold for many phenomena. In the electrical field it is valuable for measuring strain gage and thermocouple potentials, IR drops in conductors and switch and relay contacts, minute currents such as grid, photomultiplier and ionization gage currents, and very large resistances. It is also valuable for measuring potentials in both animal and plant biology as well as other chemical potentials.

CIRCUIT ARRANGEMENT

The basic circuitry of the instrument is indicated in Fig. 3. From an operational standpoint the modulator can be considered as a chopper that alternately connects and disconnects the amplifier input from the dc source being measured at a 50 cps rate. Following the modulator is a five-stage amplifier with a basic gain of 140 db. Selectivity corresponding to a Q of about 10 is incorporated in the amplifier to limit noise to well below the saturation level of the later amplifier stages.

The amplifier is followed by a synchronous demodulator similar to the modulator and by a selective filter which gives the overall instrument a frequency range of from dc to about 0.2 cps in the highest gain position. Overall feedback of at least 30 db in the highest gain position and more on lesser gain positions makes the system essentially independent of tube and line voltage effects. Output terminals in parallel with the metering circuit permit the instrument to be used as a dc amplifier with an output of 1 volt and with a maximum gain of 100 db in the most sensitive position.

To avoid disturbance of the input circuit, range changing is accomplished by varying the return gain in the amplifier feedback circuit. Eleven voltage ranges provide for measurements from ±10 microvolts full scale to ±1 volt full scale; 18 current ranges provide for measurement from ±10 μA full scale to ±3 mA full scale. All ranges are related in a 1-3-10 sequence.

BASIC SENSITIVITY CONSIDERATIONS

The use of a 50-cps carrier frequency for the amplifier combined with a narrow bandwidth makes the amplifier practically insensitive to 60- or 120-cycle voltages in the dc circuit being measured. To produce an observable offset on the meter, such voltages have to be large enough to saturate the amplifier. In

Fig. 3. Basic circuit arrangement of hp Model 425A Micro Volt-Ammeter.

Fig. 4. Typical warm-up drift characteristic of most sensitive range (10 μV full scale). One semi-major vertical chart division equals 1 microvolt. Large transient at left of records in both Figs. 4 and 5 is instrument turn-on transient. Steps in first two minutes of record are initial zero adjustments. Fine structure is noise which is basic sensitivity limitation of instrument and is rated as being less than 0.2 microvolt rms. In a record such as this, noise appears worse than when watching meter.

Fig. 5. Typical warm-up drift characteristic similar to that of Fig. 4 except on second most sensitive range (30 μV full scale).
practical terms this means that 60-
cps signals have to be well above 50
db above full scale on the three most
sensitive ranges. Even a 50 cps sig-
nal, should it be encountered, has to
be considerably larger than full scale
in order to cause appreciable error,
since the input filter has its maxi-
mum rejection at that frequency.

These considerations result in the
fact that the chief limitation on sen-
sitivity for the instrument is thermal
noise in the input circuit. Assuming
an equivalent noise bandwidth for
the system of 1 cycle, the thermal
noise from resistance in the input
circuit calculates to about 0.06 micro-
volt rms, while flicker noise referred
to the input is about 0.03 microvolt
rms. Total random noise referred to
the input is thus of the order of 0.1
microvolt. This agrees well with ob-
served results (see Fig. 4), and the
instrument is rated as having less
than 0.2 microvolt rms noise reading.

STABILITY

The performance of the instru-
ment is perhaps best summarized by
the curves shown in Figs. 4 to 6. Figs.
4 and 5 show warmup drift on the 10
microvolt and 30 microvolt ranges
at room temperature. Typical noise
readings are also visible on the rec-
ords. On the 100 microvolt range
noise readings are almost undetect-
able. The record is arranged so that
one semi-major chart division corre-
sponds to one major division on the
meter face, i.e., 1 microvolt in Fig. 4
and 3 microvolts in Fig. 5.

Typical line voltage effects on
zero shift are indicated in Fig. 6 for
a ±10-volt change from 115 volts on
the most sensitive range.

FLOATING INPUT

The instrument is designed with
an isolated chassis which can be
grounded to the cabinet if desired by
means of a grounding link at the
back. The isolated chassis, however,
permits the instrument to be used
to measure off-ground voltages such
as small differences between large dc
voltages, since the chassis can be op-
erated with up to 400 volts between
chassis and cabinet. The output ter-
minals on the rear further permit
the instrument to operate a recorder
for making drift records in such
voltage sources.

INPUT IMPEDANCE

Basically, the instrument has a
very high input impedance in excess
of 50 megohms. In order to have a
fixed input impedance to shunt for
current measuring purposes, a 1
megohm resistor is placed internally
across the input terminals, giving
the instrument a 1 megohm input
resistance on voltage measurements.
If a high impedance of 50 megohms
or more is desired, this resistor can
be omitted at the factory. Current
measurements on the more sensitive
ranges will then require either plac-
ing an accurate 1 megohm resistor

across the terminals or making measurements in terms of the IR drop across another known resistance.

The input resistance on current measurements varies from 1 megohm on the most sensitive ranges to 0.33 ohm on the least sensitive 3 ma range and is listed elsewhere herein.

OVERLOAD PROTECTION

The input circuit is arranged with a small gas tube which fires at about 70 volts to protect the instrument from accidental momentary application of voltages up to 1,000 volts between the terminals.

INSTRUMENT PROBE

The instrument design includes a special probe for connecting to the source to be measured. The probe is constructed in penholder style with clips operated by flanges on the probe body. The clips themselves are formed from metal that has a low thermal emf value to copper, the standard metal for measurement purposes.

RESPONSE AND METER DATA

The indicating meter is a large 6" zero-center type which is provided with high readability scales, as shown in Fig. 7. The movement includes a mirror scale for minimizing parallax.

For all but the most sensitive range, the response time of the instrument is essentially that of the meter movement itself which is a fraction of a second. On the most sensitive range, response time is about 2 seconds. On any range overshoot is negligible.

MEASUREMENT CONSIDERATIONS

Measuring voltages in the microvolt region often involves phenomena which are given little consideration in other work. The main effect of these factors is that unrealistic voltages will be included in the measurement. Ground currents flowing in a system under measurement, for example, can readily raise the potential at one point of a metallic ground from 10 to 100 microvolts above another point in a typical case.

Circuits involving capacitors bring into effect the matter of dielectric absorption. Most capacitors will retain portions of a charge for intervals from minutes to days and can thus introduce voltages which may need consideration.

Thermoelectric effects also introduce voltages of sizable proportions in this region. Similarly, electrochemical effects, although probably less common than the effects named above, can occur in surprising ways. Insulators such as phenolic types can produce galvanic emf's when used to support metallic studs or terminals and thus introduce error voltages into sensitive measurements.

For many of these cases the floating input of the instrument is valuable, since it enables the full sensitivity of the instrument to be used in measuring the magnitude of these effects, either in accounting for different measurements or in specific investigation of such emf's.

ACKNOWLEDGMENT

Appreciation is expressed to the people who have been helpful during the development of this instrument. John Lark and Harold Rocklitz have carried the brunt of the design assignment, and the development of the photo-conductor by Dr. H. E. Overacker's group has made the instrument possible.

—John M. Cage

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### Specifications

**MODEL 425A**

**DC MICRO VOLT-AMMETER**

<table>
<thead>
<tr>
<th>DC Voltage Ranges:</th>
<th>Eleven zero-center ranges in a 1-3-10 sequence with following full scale positive and negative values:</th>
</tr>
</thead>
<tbody>
<tr>
<td>±10 µv</td>
<td>1 m ±10 µv</td>
</tr>
<tr>
<td>±30 µv</td>
<td>1 m ±30 µv</td>
</tr>
<tr>
<td>±100 µv</td>
<td>1 m ±100 µv</td>
</tr>
<tr>
<td>±3 mµv</td>
<td>1 m ±3 mµv</td>
</tr>
<tr>
<td>±10 mµv</td>
<td>333 k ±10 mµv</td>
</tr>
<tr>
<td>±30 mµv</td>
<td>100 k ±30 mµv</td>
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<td>±100 mµv</td>
<td>33 k ±100 mµv</td>
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<td>±300 mµv</td>
<td>1 k ±300 mµv</td>
</tr>
<tr>
<td>±1 µv</td>
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<td>±3 µv</td>
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<td>±30 µv</td>
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<td>1 ohm ±1 m</td>
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<tr>
<td>±30 m</td>
<td>100 ohms ±30 m</td>
</tr>
<tr>
<td>±100 m</td>
<td>330 ohms ±100 m</td>
</tr>
<tr>
<td>±300 m</td>
<td>1000 ohms ±300 m</td>
</tr>
<tr>
<td>±1 k</td>
<td>3330 ohms ±1 k</td>
</tr>
<tr>
<td>±3 k</td>
<td>10000 ohms ±3 k</td>
</tr>
</tbody>
</table>

**Input Impedance on Voltage Ranges:**

- 10 ohms ±2%; determined by input resistor
- ±0.1, 0.3, 1 volt.

**Input Isolation:** Input terminals are floating across another known resistance.

**Power:** Operated from 115 volts ±10 volts, 60 cps; requires approx. 40 watts.

**Dimensions:** Cabinet mount: 7½" wide, 11¼" high, 14" deep. Rack mount: 19" wide, 7½" high, 10½" deep.

**Weight:** Cabinet mount, 18 lbs.; rack mount, 20 lbs.

**Shipping Weight:** Cabinet mount, 24 lbs.; rack mount, 28 lbs.

**Price:** Model 425A cabinet mount, for 60-cps line operation, $505.00; for 50-cps line operation, $500.00.

**Data subject to change without notice.**

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